Noncontact Shape Control of Membrane Mirrors

John A. Main
Jeffrey Martin
George Nelson
University of Kentucky
Department of Mechanical Engineering
521 CRMS Building, Lexington, KY 40506-0108
606-257-7137
johnmain@engr.uky.edu

ABSTRACT

Progress in development of large-scale deployable optics with integrated shape control capability is discussed in this paper. The ultimate goal of this project is the development of a large aperture adaptive optical membrane mirror that can be stowed in a small package, deployed, and then be actively corrected to the proper mirror shape for a given mission. Fundamental to the development of this large aperture optical system is a new control paradigm for adaptive structures, the electron gun controlled smart structure. Some practical aspects of electron gun control of piezoelectric materials are presented including piezoelectric material response to electron beam excitation. An experimental test bed assembled to evaluate electron gun control of PZT-5H ceramic wafers and a bimorph mirror constructed from polyvinylidene fluoride is described and results of proof-of-principal tests discussed.

Keywords: smart structures, piezoelectric, high resolution, deformable mirrors, adaptive optics

1. INTRODUCTION

Optical systems designed for orbital applications face constraints distinct from their terrestrial counterparts. Most significantly, the penalty for any satellite that is large and heavy at launch is great because the cost increase associated with stepping from a small booster to a large one is immense. For this reason a different approach to the design of lightweight optical systems for orbital use is explored in this paper. In this concept, optical components such as mirrors are formed from thin layers of active materials. The use of piezoelectric materials is explored here. The inherent shape control capability of the active material allows the optical components to be lighter and more flexible because the precise shape of the mirror can be actively maintained with feedback control.

The widely accepted approach for applying control signals to dielectric active materials such as PZT is to place electrodes on opposing sides of the block or wafer, then apply a potential difference across the electrodes. This configuration places a relatively constant electric field throughout the active material, thus stimulating the desired strain in the piezoelectric material. While this method of applying control signals has proven to be very successful in a wide range of smart structures applications, it is not without its shortcomings. Some limits on control commands naturally result when distributed electrodes are used to carry control signals, particularly if large scale active structures such as reflectors or mirror surfaces are considered. Among these limits are the following: (1) the system spatial resolution can be no smaller than the smallest electrode, thus greater spatial resolution requires more electrodes and wire leads, and (2) the boundaries of the area where a shape correction is to be applied must correspond with the boundaries of one or more electrodes.

The solution to these problems explored in this paper is a non-contact control method utilizing an electron gun to apply charge and stimulate piezoelectric strains. Applying the control signals in this fashion eliminates the need for the electrode pattern, thus the constraints posed by electrodes are eliminated. This method of application of control signals to piezoelectric materials may be traced back as far as acoustic sensors designed by Brown and Sivyer in 1975. Also Hubbard (1992) developed an adaptive pellicle mirror using the electron gun approach. Despite this previous work, comprehensive engineering information on the electron gun approach to smart material shape control is not available. This current investigation emphasizes the development of an engineering foundation for electron gun control of smart materials.

2. DEMONSTRATION OF ELECTRON GUN STRAIN CONTROL

A simple proof of concept experiment was assembled to demonstrate and investigate electron gun control of smart materials. A schematic of the experimental setup is shown in Figure 1. The principal components are the electron gun, PZT target which could be a mirror or large reflector constructed from piezoelectric materials, strain sensors, and the back pressure power amplifier. Each of these components is discussed in more detail in the following paragraphs. Note that the electron gun and PZT target are placed in a chamber evacuated by a roughing/turbomolecular pump system to 2e-6 torr. This prevents filament burnout in the electron gun. A photo of the electron gun and PZT target is also included as Figure 2.

2.1 Electron Gun System

The electron gun used in this study is a commercially available model (Kimball Physics EFG-7). This apparatus and accompanying amplifier provide the capability to project an electron beam with beam energy adjustable between 0 and 1500eV. Beam current is also continuously adjustable between 0 and 100 μA. Focus control is provided to maintain a tight beam spot at a variety of energy levels, and the beam may be deflected and aimed over approximately a 10cm x 10cm area at a gun to target range of 15 cm. The flexibility of this system is one of its principal advantages in this research effort, as all beam input parameters, energy, current, focus, x- and y-deflection, may be manipulated manually or through direct input from an external controller.

2.2 PZT Target

Wafers of PZT-5H were used in the initial experimental evaluation of electron gun control. The 4 cm x 6 cm wafers are 1 mm thick with the 3-direction corresponding to the thickness dimension. The manufacturer provided the piezoceramic wafers with nickel-silver electrodes applied on both sides. The positive electrode was removed from each test specimen by swabbing with nitric acid and then sanding lightly. A single wire lead was attached to the remaining electrode which was then connected to the 'back pressure' amplifier.

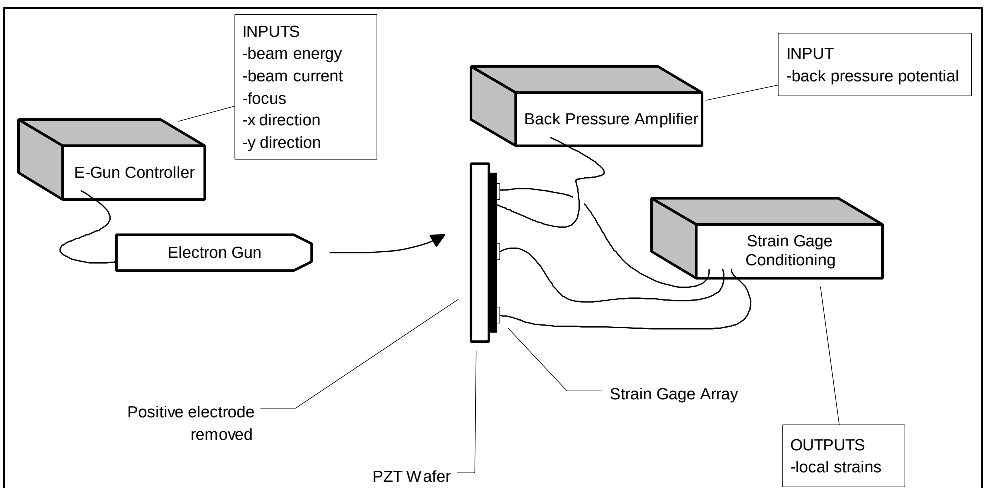

Figure 1. Schematic of the electron gun experimental setup.

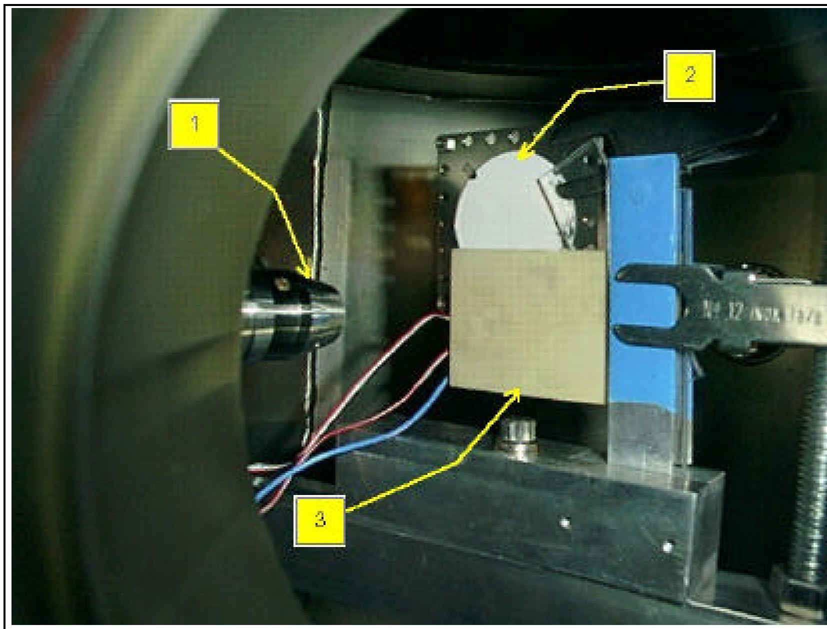

Figure 2. Photo of the electron gun (1), phosphor screen for checking beam directional control (2) and the piezoelectric material target (3).

Within the vacuum chamber the sample plates were clamped on one edge and oriented to expose the unelectroded (positive) face to the electron flux. The plates were typically placed 12 to 15 cm from the electron gun.

2.3 Back Pressure Amplifier

A power amplifier was connected to the single remaining electrode on the piezoelectric wafer. The amplifier used here was capable of controlling the potential of the electrode from -200 to +200 V. This voltage source is referred to as the "back pressure" amplifier because it is used to manipulate the potential on the side of the piezoelectric material away from the electron gun.

2.4 Piezoelectric Strain Sensor

Electrical resistance strain gages were affixed atop the back pressure electrode in order to sense the piezoelectric strain stimulated by the electron gun.

2.5 Piezoelectric Strain Control

In this investigation initial efforts focused on manipulating the energy of the electron beam to stimulate positive and negative surface charges. The change in surface charge that results from the collision of an electron with the surface of a piezoelectric material is not as simple as the addition of one electron-sized negative charge. An electron is decelerated when it impacts a surface, giving up its kinetic energy to the material. A number of things can happen to that energy, including raising the energy levels of other electrons to the point that they are ejected from the surface. These electrons are known as secondary electrons. The number of secondary electrons emitted from a surface due to the impact of a single electron is a function of the energy of the incident electron.

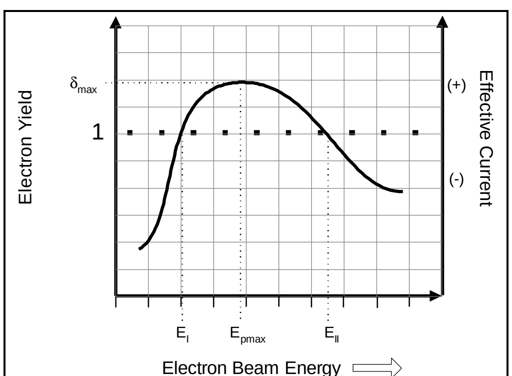

Figure 3. Secondary electron yield for a typical dielectric.

Figure 3 shows a plot of the secondary electron yield for a typical dielectric material as a function of the incident electron energy.

Our initial foray into electron gun control of piezoelectric strains attempted to take advantage of the fact that the secondary electron effect gives a variable energy e-gun the ability to apply net positive and net negative charges to the surface of the piezoelectric material. Hubbard (1992) also used this approach. If the electron gun emits electrons with energies that cause an electron yield greater than one, this should cause a net (+) charge to accumulate on the dielectric surface. The opposite effect should be observed when the incident electrons have energies such that the yield is less than one. If the electrode is maintained at a constant potential the net result is that both (+) and (-) electric fields can be applied to the active material.

While theoretically sound, some practical problems were encountered early in the investigation when direct strain control via electron beam energy (and thus the surface charge) was implemented. The ability to stimulate both positive and negative strains by adjusting the beam energy was confirmed by using the experimental apparatus shown in Figure 1 and defocusing the electron beam such that it flooded the PZT sample. Piezoelectric strains were both applied to and removed from the entire sample by manipulating the beam energy. However, when the beam was focused to a small point, and the same process was attempted, it became obvious that variations in beam energy coupled through to the other input parameters, in particular the beam focus and x- and y- beam direction. The changes in beam direction and focus were significant when the beam energy was varied, making control of the strain of a specific spot on the piezoelectric wafer virtually impossible without constant user intervention. While it is certainly possible to diminish or eliminate these coupling effects using feedback control, logic dictates that if a control strategy were to be found which avoided the coupling entirely it would likely be the preferred option.

Faced with this problem a variety of alternative control approaches were explored. From this exploration a viable alternative to beam energy control emerged. The heart of the new approach is the use of an electron beam of constant energy, thus avoiding the energy-deflection coupling. Control inputs are applied by actively manipulating the potential of the "back pressure" electrode.

As an example of the utility of back pressure control a sample of piezoelectric material was subjected to controlled electron gun inputs and back pressure potentials and the resultant strains recorded. The inputs and resulting piezoelectric strains are shown in Figure 4. The strain reading shown in the top plot is from a strain gage mounted on the back pressure electrode. 200 eV electrons were used in this test.

The electron beam current, back pressure potential, and piezoelectric strain all begin at zero. The back pressure potential is then increased to 100 V, but the piezoelectric strain does not respond because the circuit is not closed. However, when the electron gun is activated and the beam current begins flowing a sudden increase in piezoelectric strain is measured by the strain gage which quickly plateaus at

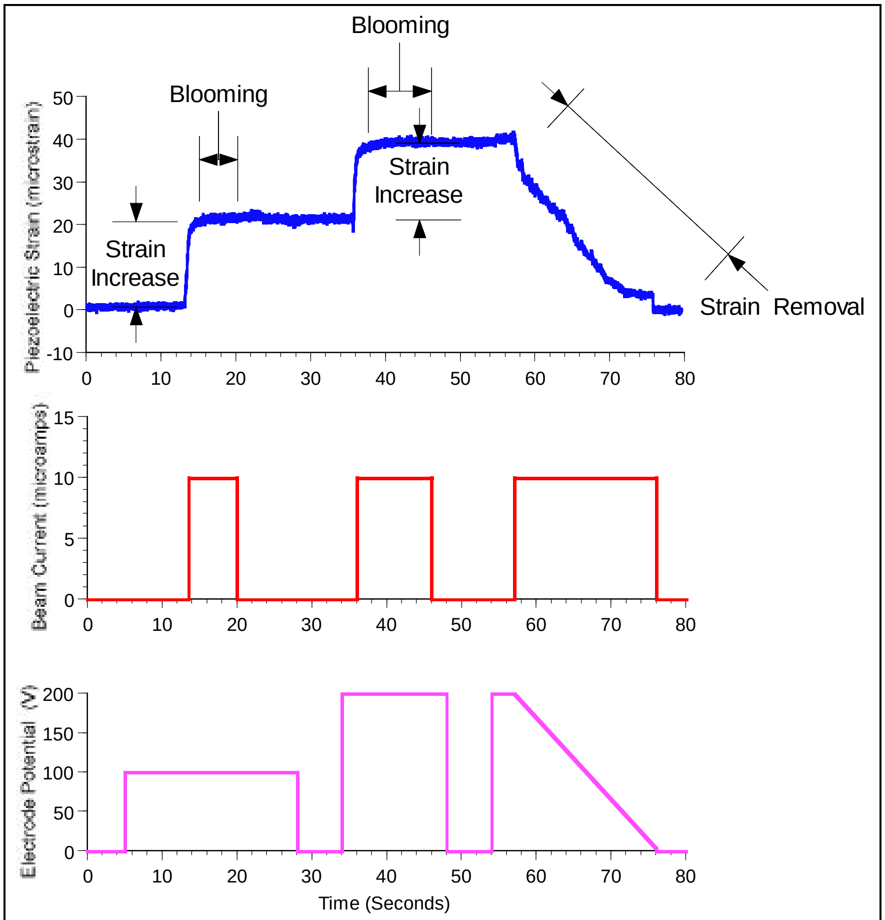

Figure 4. Permanent strains imparted to piezoelectric materials using an electron gun and back pressure control.

approximately 20 μstrain. An important fact to note is that this strain remains present in the material upon removal of first the beam current, and then the back pressure potential.

The next step in the piezoelectric strain plot occurs when the electron beam is activated in the presence of a 200 V back pressure potential. The strain increases to approximately twice the 100 V level and again the strain remains in the material upon removal of the electron beam and back pressure potential.

Experience demonstrated that removal of the strains from the PZT-5H sample is a bit trickier. Before the piezoelectric strain can be changed, the current must be reestablished. This requires raising the potential of the back pressure electrode to the level which caused the present piezoelectric strain. Once the current is established the backside pressure is ramped down. The piezoelectric strain was observed to follow the same ramp profile when this was done.

2.6 Observations from PZT Electron Gun Tests

Rigorous engineering models for the interaction between the electron gun, active material, and the back pressure potential have yet to be formulated, yet some conclusions can be drawn from the data on hand.

- Shape changes can be imparted and removed upon command.
- Shape changes are not transient. They remain after the electron beam is broken and electrode potential removed.
- There is a quasi-linear relationship between back pressure potential and piezoelectric strain.

3. FLEXIBLE MIRROR TEST BED

Based upon the successful demonstration of electron gun shape control outlined above, a similar experimental investigation was undertaken to evaluate the use of this control method in optical systems. To this end a membrane mirror was fabricated and the control responses observed when the mirror was subjected to an electron gun shape control input.

3.1 Bimorph Mirror

A PVDF (polyvinylidene fluoride) bimorph was chosen to perform the function of a shape-controlled membrane mirror for this demonstration. While PVDF is unsuitable for use in the aerospace environment, it was chosen for this work because it is inexpensive and readily available. Piezoelectric polyamides, which promise to be more tolerant of the space environment, are currently under development as are a wider range of piezoelectric ceramics.

The PVDF mirror was constructed from a two-layer bimorph as shown in Fig. 5. The bimorph design allows the curvature of the bimorph to be controlled by manipulating the electric field across its thickness.

These PVDF bimorphs were fabricated from 52 μm sheets, and the glue layers are also on that order. The bimorph mirror used in the tests described here is 10 cm long and 5 cm wide. The direction of the primary strain response of the PVDF was in the longitudinal mirror direction.

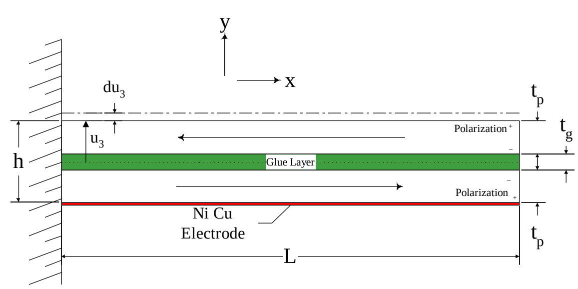

Figure 5. Edge view of the piezoelectric bimorph membrane mirror.

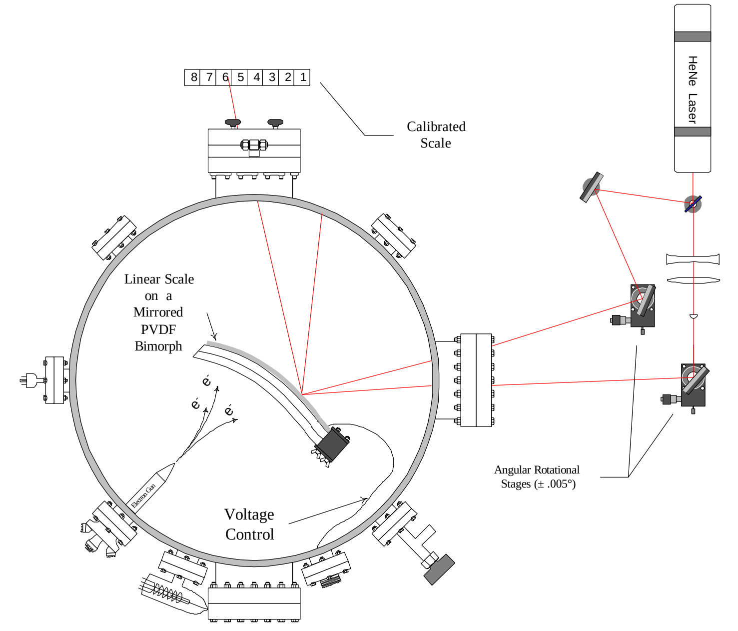

Figure 6. Electron gun controlled bimorph PVDF mirror system.

3.2 Electron Gun Bimorph Mirror Demonstration

The use of the applied back pressure voltage on the electrode in conjunction with the electron gun's ability to focus on finite points enables point specific adjustments of the membrane mirror. The following series of experiments were executed to demonstrate this capability on a PVDF bimorph mirror. The bimorph used in this study has a single, nickel-copper alloy electrode on one face of the bimorph which doubles as a mirrored surface while the surface subjected to the electron flux is left bare. Figure 6 shows the experimental setup and also illustrates the triangulation scheme used to determine the shape of the active mirror. A photo of the bimorph mirror mounted in the vacuum chamber is also included as Figure 7.

3.3 Flood Beam Mirror Control

The electron gun used in this study is capable of placing a focused electron beam anywhere on the bare surface of the membrane mirror with a variable electron energy range of 10 - 1500 eV. The back pressure amplifier is capable of applying a variable potential between -1000 and 1000 V to the mirror surface electrode. Initial tests of the bimorph mirror were performed subjecting the entire bare surface of the bimorph to the electron flux.

With the gun set to evenly distribute 800 eV electrons over the surface and the back pressure amplifier activated, mirror profiles were measured over a range of back pressure potentials. Figure 8 shows some results from these tests. Each curve in Figure 8 illustrates the dependence of the mirror deflection upon the back pressure potential applied to the electrode. Note that the resolution of the measurement technique used was approximately 0.5 mm, so the deflection of points near the base is difficult to discern. The overall trend is clear, however, and it is obvious that the mirror curvature is changing in response to the electron gun and back pressure potential inputs.

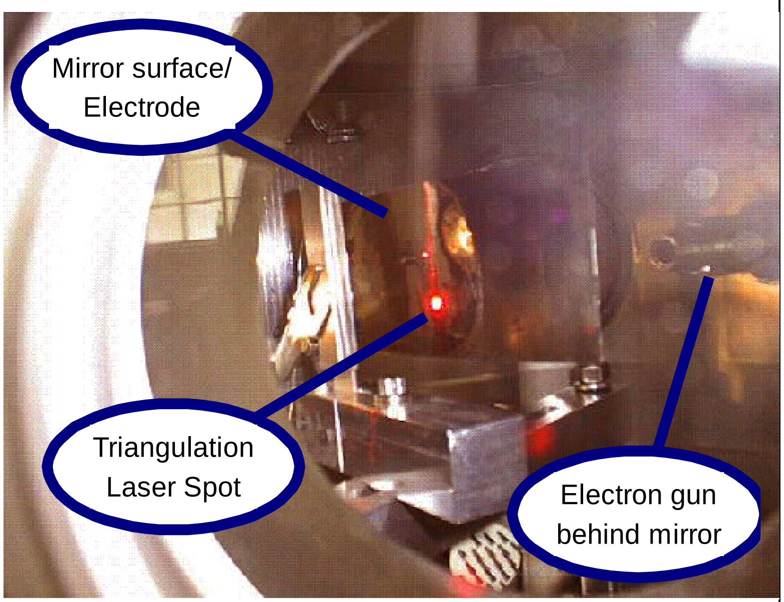

Figure 7. Photo showing the bimorph mirror in the vacuum chamber.

3.4 Controlling Discrete Areas

This simple experiment was contrived to illustrate the ability of electron gun control to address discrete areas on the surface of the membrane mirror. First, the membrane mirror was flooded with 800 eV electrons over its entire surface with the back pressure potential held to 0. This was done to ensure that all portions of the mirror shared the same initial conditions. The beam was then adjusted to cover a

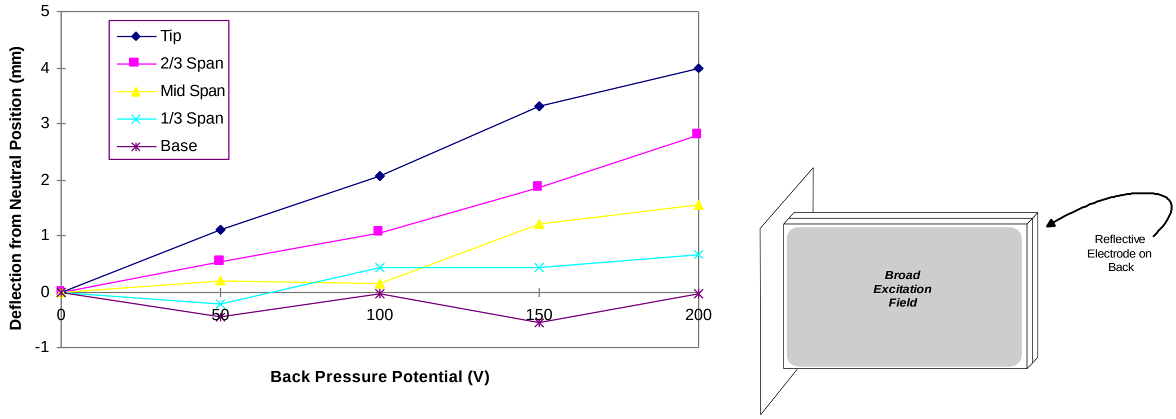

Figure 8. Deflection of various points along the length of the mirror as a function of the back pressure potential. A flood electron beam was used to irradiate the entire bare side of the PVDF.

1-cm wide strip near the end of the cantilever. Then the V_{bp} was adjusted to 700 volts and the tip deflection determined via triangulation. This procedure was repeated 4 times. Between each, the mirror was flooded with 800 eV electrons and 0 V_{bp} to return the mirror to a neutral position.

The electron beam was then refocused and the strip beam target area was incremented slightly toward the mounting base of the membrane mirror and the procedure repeated. The deflection of the tip of the mirror as a function of excitation location was determined by performing this experiment at 14 separate positions. The results of this experiment are shown in Fig. 9. The experimental curve in the figure shows the tip deflection as a function of the location of the excitation beam. If the electron beam is actuating only a discrete area the closer the beam is to the base the larger the tip deflections should become. The data indicates that applications of the beam at the tip cause very little deflections and excitation at the base very large deflections, thus verifying that electron gun control can be used to activate discrete areas.

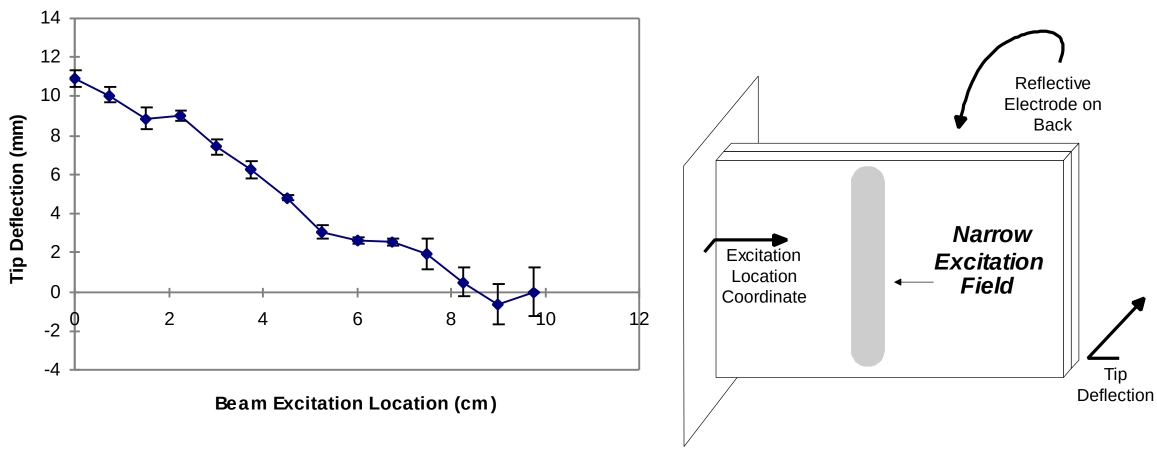

Figure 9. Tip deflection of the mirror as a function of excitation field location. Note that the curvature control can be limited to a discrete area.

3.5 Observations from Bimorph Mirror Electron Gun Tests

- Curvature of a piezoelectric bimorph mirror with an electron gun can be accomplished. Sufficient shape control was achieved to change the tip location of a 10-cm long membrane mirror 0.4 cm. Greater deflections are possible with higher back pressure voltages.
- Discrete areas of a continuous structure can be controlled with an electron gun.

4. ACKNOWLEDGMENTS

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5. REFERENCES

Brown, P.H. and R.F. Sivyer, "Cathode ray tube acoustic transducers," U.S. Patent #3899709, August 12, 1975.

Hubbard, J., "Active Mirror Assembly," United States Patent #5,159,498, October 22, 1992.